*32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-4.072 (2005)*

Extending the operational range of improved H-modes at ASDEX Upgrade

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1. Introduction

The principal reference scenario for ITER [1] is based on H-mode operation. It provides the foundation for achieving ITER's primary goal of inductive (pulsed) operation at Q=10. Alternatively, advanced scenarios in fusion experiments seek to improve confinement and stability over standard H-modes in order to provide long pulse or fully non-inductive regimes. Key to the development of these scenarios is the tailoring and control of the current density profile.

Since 1998 ASDEX Upgrade has developed a stationary regime of operation called "Improved H-Mode". This regime has a stationary q-profile with q_0 at, or slightly above, 1 with low magnetic shear in the centre and q_{95} ~ 4. Improved H-mode discharges are typically obtained at low density (~40% of the Greenwald density, n_{GW}), sawteeth are absent and (3,2) neo-classical tearing modes (NTMs) remain small at high beta. This enables routine operation up to β_N ~3 with $H_{98}(y,2)$ up to 1.4 [2]. The available pulse length for the heating and power supply systems mainly limits the duration of these pulses at ASDEX Upgrade to a maximum of 50 energy confinement times (several current diffusion times).

Further developments of this regime in recent years, by various experiments, have been performed under the common name "ITER Hybrid Scenario". The flexible heating, fuelling and poloidal field systems at ASDEX Upgrade allow experiments to explore the operating conditions for improved H-modes. The tools available include 20 MW neutral beam power with central and off axis beam deposition, up to 5 MW of ion cyclotron resonance heating and the use of electron cyclotron resonance heating at 140 MHz, with up to 1.2MW of total input power. Recent experiments at ASDEX Upgrade focussed on extending the improved H-mode regime to values of q_{95} from 3 to 5, and on operation at high electron density. The results of these experiments, co-ordinated by the International Tokamak Physics Activity (ITPA), are reported in this paper.

2. Improved H-modes for an extended range of q_{95}

The figure of merit for fusion performance $H_{98}(y,2)\times\beta_N/q_{95}^2$ is approximately 0.20 for the inductive ITER reference scenario at Q=10. Here the confinement enhancement factor, $H_{98}(y,2)$ is used, typical when reporting on type I ELMy H-modes at ASDEX Upgrade. As reported previously [2], improved H-modes in ASDEX Upgrade achieve $H_{98}(y,2)\times\beta_N/q_{95}^2$ ~ 0.20 at q_{95} ~ 4. An interesting question is how this regime performs at different values for q_{95}, since the stability and confinement of advanced scenarios are linked to the current density profile. Figure 1 shows results of improved H-modes for a range of q_{95} between 3

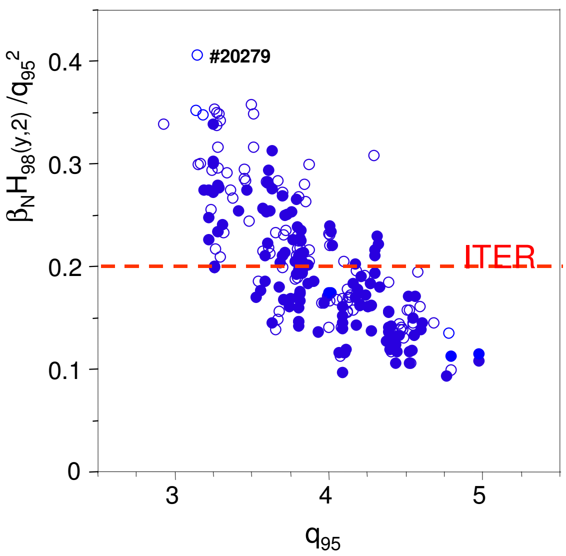


Figure 1: Performance of improved H-mode discharges at ASDEX Upgrade for $3 \le q_{95} \le 5$. Transient discharges (open symbols, duration of the high performance phase < $10\tau_E$) and stationary results (duration $\ge 10\tau_E$, closed symbols) are given.

and 5. By using the plasma start-up scenario developed for improved H-modes at ASDEX Upgrade, utilising moderate NBI heating during the current rise, good performance can be maintained for $3 \le q_{95} \le 5$. Discharges at q_{95}~5 achieve high values for beta poloidal (~2). ASTRA code analysis of the kinetic data, including models for the bootstrap current and beam driven currents, indicate that these discharges obtain a total non-inductive current drive fraction of 73%, with 40% bootstrap fraction and 33% driven by neutral beams. This shows the potential of significantly extending the pulse length in ITER Hybrid scenarios at q_{95}=5, albeit at reduced performance ($H_{98}(y,2) \times \beta_N / q_{95}^2$ ~ 0.1-0.15). In recent experiments $q_{95} \approx 3$ was obtained by raising the plasma current to 1.2MA at 2.0T, so far plasma currents up to 1MA have been used for improved H-modes at ASDEX Upgrade. Figure 2 shows an example of a discharge where the neutral beam heating is started during the current rise phase. With increasing input power β_N continues to increase, despite (3,2) NTM activity (even MHD mode activity indicated in red in Figure 2), until the discharge approaches the no wall limit (β_N = 3.1, or 4li) when a (2,1) NTM appears and locks. The locked mode signal is used to initiate a safety algorithm, whereby a large amount of neon gas is injected into the plasma in order to trigger a disruption with low forces to the vessel. Sawteeth are only observed after 2.5 seconds, mixed with fishbone activity lasting throughout the high power-heating phase, indicating that q approaches 1 in the centre. However, no large (3,2) NTMs are triggered by these sawteeth, as observed in experiments in DIII-D [5] and JT-60U [6] with q_{95} near or below 3. The confinement enhancement factor increases with power, also typical of improved H-modes at ASDEX Upgrade [2,3]. The discharge in Figure 2 achieves

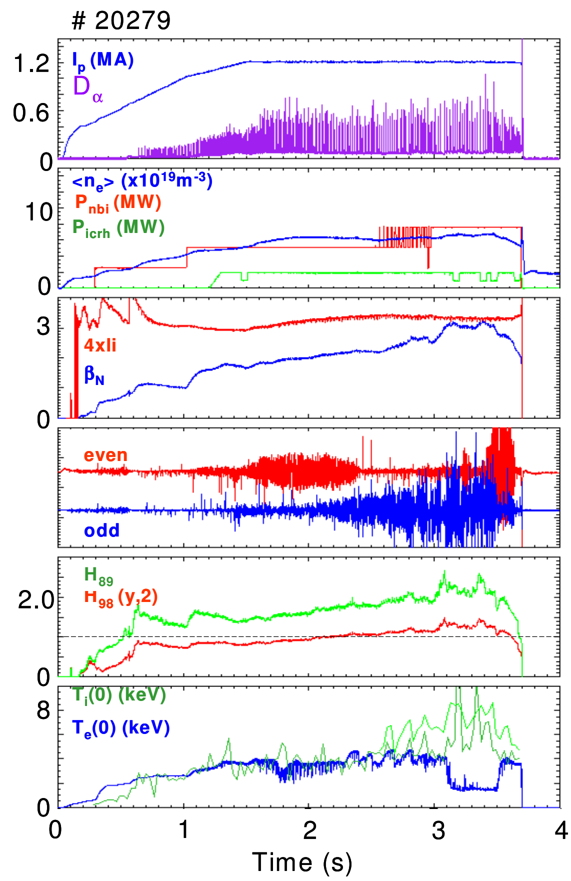
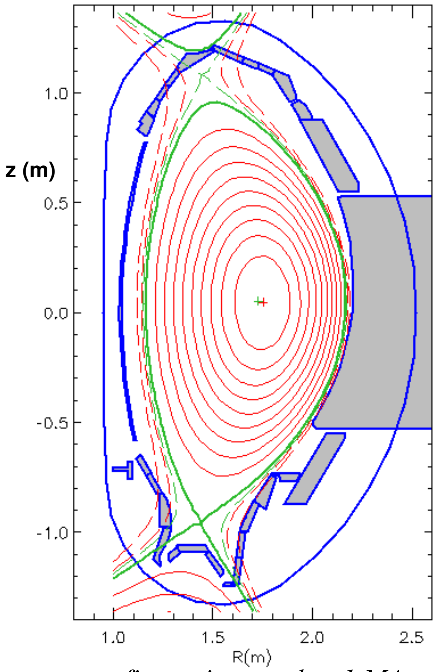


Figure 2: Improved H-mode at q_{95}=3.15.

$H_{98}(y,2)\times\beta_N/q_{95}^2$ =0.4, without the need for active control of the current density profile or MHD activity, similar to reports from DIII-D [5]. So far, experiments with q_{95} = 3.15 have obtained stable operation at β_N ~ 2.8.



configuration used at 1 MA.

3. Operation at high density

In the past ASDEX Upgrade has shown improved H-mode results at high plasma density [2]. These discharges achieve β_N values up to 3.5 at plasma currents of 800 kA. Recently, these experiments have been continued at 1MA, using a plasma configuration with high triangularity (up to 0.4) and a capability of operation near double null (Figure 3). Operating at densities of 1.1x 10^{20} m^{-3} (85%-90% of n_{GW}), these discharges achieve stable operation at β_N=3, which is 85% of the no-wall limit in these conditions, with $H_{98}(y,2)$ ~ 1, and $T_{i0} = T_{e0}$.

Covering a range of electron densities from $0.4\text{x}10^{20}$ m^{-3} to $1.1\text{x}10^{20}$ m^{-3}, the data from ASDEX Upgrade can be extrapolated to ITER using dimensionless parameters such as the normalised collisionality ($\nu^* \sim a^7\langle n_e\rangle^3\kappa^2/\varepsilon^3 W^2$, with $\langle n_e\rangle$ the average electron density). In Figure 4 the confinement improvement over $H_{98}(y,2)$ scaling is plotted versus ν^*/ν^*_{ITER} (using values given in [1]), showing that high values of $H_{98}(y,2)$ are obtained at ITER relevant ν^*. Clearly a comparison with standard H-modes at the same ν^* would be desirable. At these low densities, the density profiles are peaked [7].

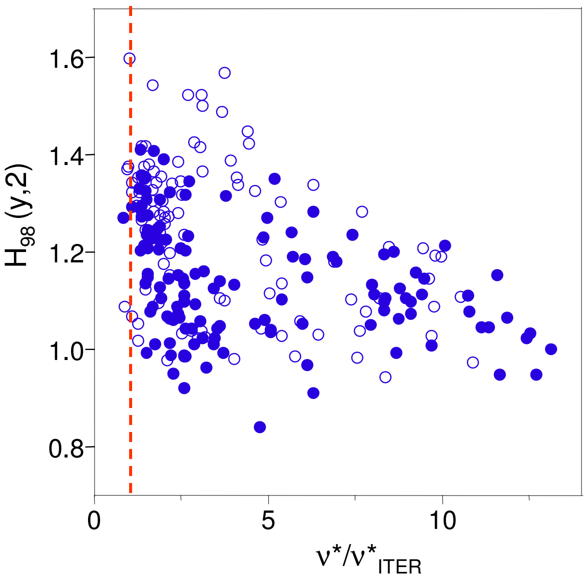


Figure 4: Confinement enhancement factor $H_{98}(y,2)$ versus collisionality (defined in text), normalised to the ITER collisionality. Transient (open symbols) and stationary results (closed symbols) are given.

The recent experiments at high density are at ν^*/ν^*_{ITER} =10-12. However, together with using near double null plasma configurations, ASDEX Upgrade typically obtains a reduction in type I ELM activity in these conditions. Phases of mixed type II/type I ELMs are observed in these new experiments at 1MA, or pure type II phases in previous experiments (800 kA) [2].

4. Performance limits: MHD stability

The stability of improved H-modes plays an important role when extending the operational domain over a wider range of q_{95} and to higher values of the plasma density. The achievement of high values of $H_{98}(y,2)\times\beta_N/q_{95}^2$ results predominantly from the fact that β_N ~ 3 can be achieved in nearly all experimental conditions explored so far. At high density (high triangularity) the maximum β_N obtained is typically in excess of 3. This compensates for the slight loss in confinement at higher ν^* ($H_{98}(y,2) \sim 1.0$) , so a similar figure of merit for fusion performance compared to discharges at lower density is obtained. Figure 5 shows that the maximum values of β_N obtained show no dependence on q_{95}. Moreover, these values

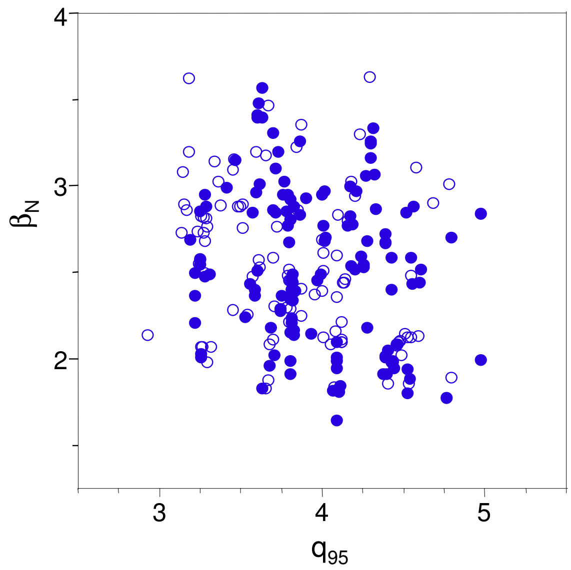


Figure 5: Values for β_N obtained at different q_{95}. Transient (open symbols) and stationary results (closed symbols) are given.

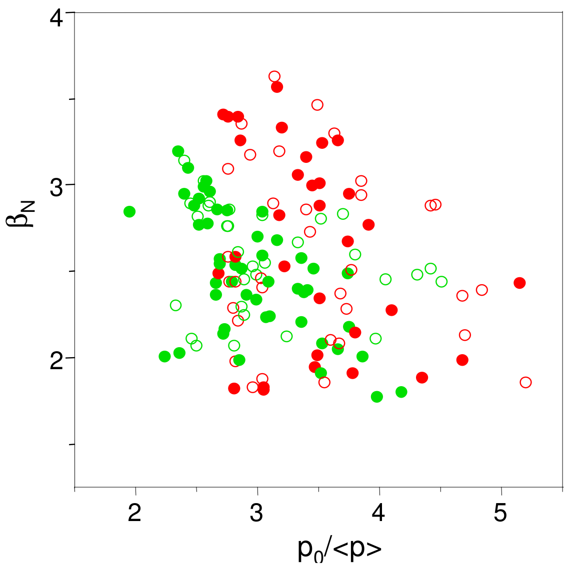


Figure 6: β_N as function of the pressure peaking factor p_0/<p>. NBI heated (red symbols), NBI+RF heated (green symbols)

of β_N are close to the no wall beta limit over the range of q_{95} explored. The improved H-modes in ASDEX Upgrade also support previous studies [8] that the maximum β_N obtainable drops sharply for high pressure peaking (p_0/<p>) calculated using central density, central temperatures and stored energy, W, see Figure 6. Compared to advanced scenarios using a reversed q-profile and internal transport barriers [9], improved H-modes have a broader pressure profile [3], favourable for obtaining high beta. Some improved H-modes in ASDEX Upgrade use central heating with ICRH or ECRH (green points in Figure 6) to reduce peaking of the density profile (and hence pressure peaking factor) to optimise the achievable beta. The beta limit in improved H-modes manifests itself as a (2,1) NTM, while (3,2) NTMs can be present without detrimental effects. The role of (3,2) NTMs in improved H-modes is not clear. DIII-D reports that (3,2) NTMs are important in sustaining the q-profile with low magnetic shear in the centre [5] whereas in ASDEX Upgrade the situation is still unclear [4]. Hence documentation of the role of NTMs in improved H-modes (Hybrid scenarios) is one of the themes for further international collaboration studies under the ITPA.

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